

MULTISTAGE PULSE TUBE REGRIGERATION CHARACTERIZATION OF THE NORTHROP GRUMMAN HIGH CAPACITY COOLER—AN UPDATE

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MULTISTAGE PULSE TUBE REGRIGERATION CHARACTERIZATION OF THE NORTHROP GRUMMAN HIGH CAPACITY COOLER - AN UPDATE

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ABSTRACT

The characterization of a multistage Pulse Tube cycle refrigeration system has been partially performed on the Northrop Grumman High Capacity Cooler (NG HCC) cryocooler by the Air Force Research Laboratory. This cooler's design uses two pulse tube cold ends in parallel. The nominal 85 K cold end is thermally strapped to the regenerator housing of the nominal 35 K cold end in order to boost 35 K cooling capacity. The cooler was tailored to support long wave infrared (LWIR) HgCdTe focal plane arrays and their associated optical systems, but this particular refrigeration system can also support a variety of short or medium wave infrared sensing as well as high temperature superconducting electronics applications. The results are presented for both steady state and transient performance envelopes for this cooler on and off the design point of 2 Watts of cooling at 35 K and 17 Watts at 85 K. When it is off the design point the load is up to 15 Watts of cooling at "35 K" and 50 Watts on the "85 K" sides. Testing off the design points will indicate the applicability of this cooler to other systems. These results are presented both as empirical data and as interpolating function estimates of the entire performance envelope.

KEYWORDS: cryogenic, cryocooler, refrigeration, pulse-tube, exergetic cooling

INTRODUCTION

The widespread introduction of space flight quality cryogenic refrigerators into the trade space for a variety of missions has brought increased interest into designs which can support multiple cooling loads at various temperatures. While these devices' potential benefits have been discussed in detail in the past[1], what has not been investigated thoroughly is a description of the performance of these devices and how these vary from

cooler to cooler. The NGST High Capacity Cooler (HCC) is one of these multi-load cryocoolers that has the potential to impact future payloads, however its performance varies greatly in comparison with past studies on the Ball Aerospace SB235[2]. This paper will attempt to give an overview of the characterization of the HCC to date.

PERFORMANCE MAPPING OF HCC

The performance mapping of the HCC was performed on a wide variety of loads. Many of these loads are far outside the design specifications for this cooler. However, because of the possibility of unanticipated high loads occurring on orbit such as during a radiative event and the possibility of this cooler being used on multiple payloads, this testing is necessary. Testing was performed while assuring that no cold head reached a temperature over 200K.

HCC was designed to perform at the very edge of its performance envelope which is at the design point of 35K and 85 K. The data in Figure 1 is presented in a format which allows a payload designer to know the load availability for given temperatures. It is important to note that this test holds the load on one stage steady, while varying the load on the other stage.

LOW TEMPERATURE STABILITY

A predictable low stage temperature is a requirement for the focal plane array (FPA) since temperature variation can lead to dark current variation (unexpected noise). The results of the HCC low temperature stability in Figure 2 was taken after 365 hrs of continuous operation. The mid-stage has a cyclical temperature variation that has persisted through out the testing of this cooler. This could be because of natural harmonics in the regenerator, or more likely the air conditioning slowly turning on and off, affecting thermometer calibration. The source of this anomaly is under investigation.

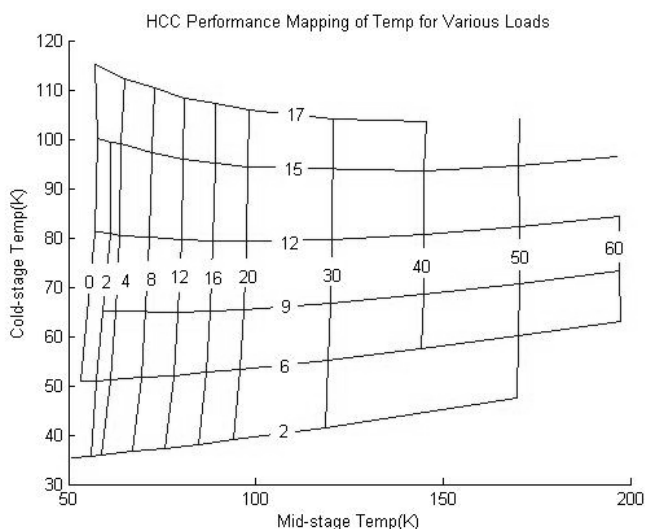


FIGURE 1. Performance Mapping of HCC in Watts (TR 300 K, 43.7 Hz, Varied Power).

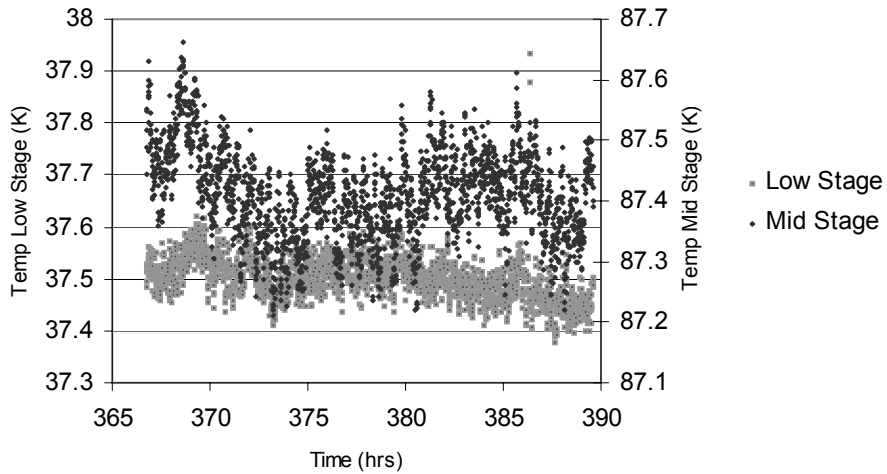


FIGURE 2. Low Temperature Stability (TR 300 K, 2W and 17W, 43.7 Hz).

COMPARISON TO BALL SB235

Performance comparisons of single stage coolers have been detailed in the past [3] but the single stage analysis does not directly extend to a multi-stage cooler. The reason for this is the amount of data required to compare multistage coolers is seemingly insurmountable. Also the inherent differences of the coolers would make comparing temperature and load data virtually meaningless. One solution as presented by Razani [4] is to compare exergy vs. exergetic efficiency (percent Carnot).

$$Q_{cooling,exer} = \sum_{i=1}^n Q_i \left(\frac{T_{rej}}{T_{cooling,i}} - 1 \right) \quad (1)$$

$$\eta_{exer} = \frac{Q_{cooling,exer}}{P_{input}} \quad (2)$$

Where $Q_{cooling,exer}$ is the total exergy delivered to all refrigerated reservoirs and η_{exer} is the exergetic efficiency of the cryocooler.

The Ball SB235 cryocooler's performance has been discussed in prior literature [5], it is a Stirling and not a pulse tube cryocooler. While this technology is significantly different from the HCC (dual pulse tube), both coolers have two stages, where part of the exergy of the mid-stage is used to "pre-cool" the cold-stage. The result is a high efficiency cooler that can reach much colder temperatures than a single stage refrigerator would otherwise.

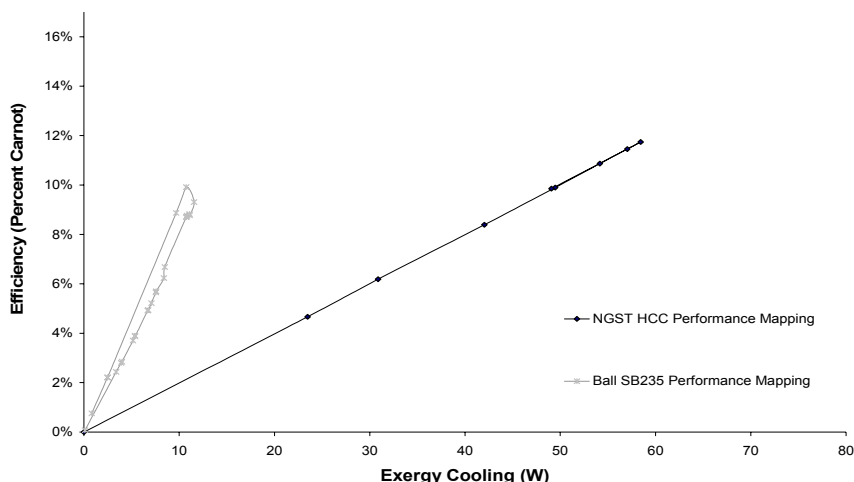


FIGURE 3. Efficiency as % of Second Law limit as a function of Exergetic Cooling. (TR 300K, 43.7 Hz, 82% stroke)

An exergy vs. Carnot comparison of the SB235 and the HCC is shown in Figure 3. The loop for the HCC extends to approximately 60W as compared to the 10W of cooling capacity for the SB235. This does not mean that the HCC is necessarily a “better” cooler it just means that if 60 W of cooling is needed then it is about 12% of carnot. However, if a cooler was needed in the 10W exergetic cooling region the HCC would not be chosen because the SB235 has higher efficiency in that cooling regime. This is partly due to the efficiency of a pulse tube vs. stirling cycle at these temperatures. Both of these coolers also have exergy “loops” although the HCC has a tight exergy loop. The result of the tight loop is that the HCC has very little trade off available between exergy and efficiency, while the SB235 there has more trade off available. The SB235 also exhibits a distinct maximum for both efficiency and total cooling implying that there exists a neighborhood in which cooler operations may be described as “optimal”. Such a neighborhood does not exist for the HCC.

FREQUENCY VARIATION

The HCC was designed to operate at 43.7 Hz, however, different system applications of the same cooler might operate with more exergetic cooling or with more efficiency at different frequencies. The first test, (Figure 4) shows the point of maximum efficiency while holding the cold stage temperature steady. As is to be expected, as the cooler operates at colder temperatures it operates less efficiently. What is interesting is that as the temperature of the cold stage is increased the efficiency becomes more steady regardless of frequency. This is because as the cooler requires more exergy to maintain a lower temperature, and it gets farther from the optimal frequency the efficiency decreases more rapidly.

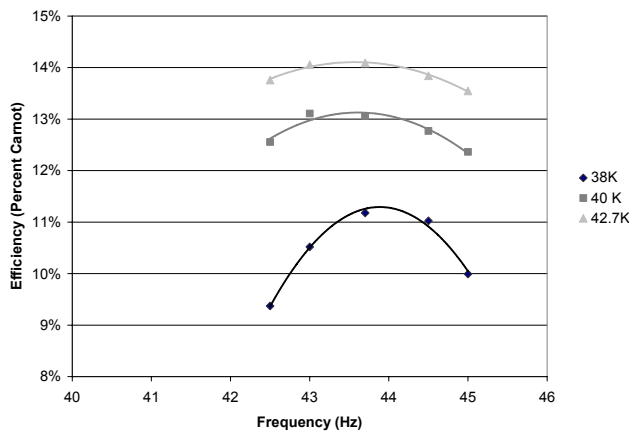


FIGURE 4. Frequency vs. Efficiency (TR 290K).

In order to get the exergy vs. % carnot loops it was necessary for the variable value to be the mid-stage load, while holding all other values steady. The results of this test are seen in Figure 5. One of the advantages of using the exergy vs. % of carnot efficiency graphs is that it clearly shows how close to the maximum exergy and efficiency the design point is. The HCC design point of 2W and 17 W on the graph is about 11% of carnot on the 43.7 Hz loop. This is close to the point of maximum exergy and efficiency and this illustrates how carefully designed the HCC is for its operational set point. In order to get more exergy and efficiency sacrifices in the minimum temperature and corresponding increases in load have to be made. What this graph also shows is that there would be little value in changing the frequency from 43.7 Hz. Any change in frequency which might increase the efficiency by a small amount would result in a significant decrease in available exergetic cooling.

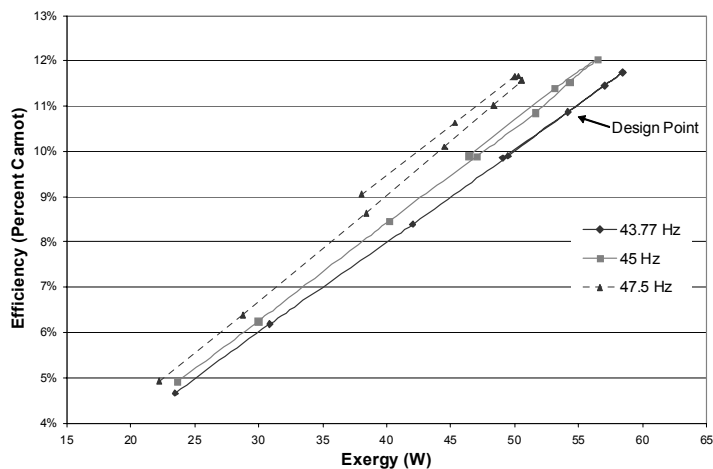


FIGURE 5. Efficiency as % of Second Law Limit as a function of Exergetic Cooling (TR 300K, 80% stroke).

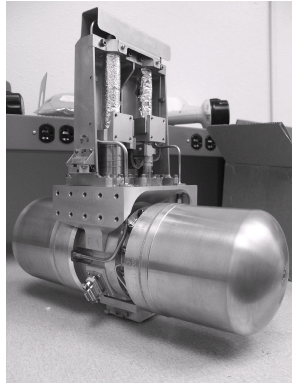


Figure 6. Northrop Grumman High Capacity Cooler.

REJECT TEMPERATURE DEFINITION

It is generally understood that the temperature reject (T_{rej}) is the temperature of the cooler base plate. However, where on the base plate it is measured can impact system level designs. Originally, the HCC reject temperature was measured in between the two pulse tubes, so when the cooler was running at maximum capacity (2W and 17W, 35K and 85K) the TR was 300K. However, at the edge of the cooler where the radiator conductive link picks up rejected heat, the temperature was 290K. The resulting cooler specifications had limited application to system level designs. The definition of T_{rej} , which is used for this paper, is the average of the temperatures at the four corners of the baseplate. This is on average about a 10K difference from in-between the two pulse tubes. The data presented reflects this change and future coolers including the NGST HCC flight qualification cooler are being designed to address the issue of the large baseplate temperature gradients.

CONCLUSIONS AND FUTURE WORK

The principal direction of this investigation in the future will be to discover how the cooler proportions energy between pulse tube sides and to continue characterization. What is left in the characterization of the HCC is the thermal vacuum proto-qualification trial, cold end temperature stability trials, transient thermal environment response, and endurance testing.

Also, a continuation of the comparison of various refrigeration systems will be made between the Ball SB235, NGST HCC, and eventually Raytheon RS2P systems, which will demonstrate the inherent performance differences among these multistage systems.

NOTATION

η	<i>efficiency</i>
Q	<i>cooling load</i>
T	<i>temperature</i>
P	<i>power</i>

Subscripts

c *cooling*
exer *exergetic*
in *input*
rej *rejection*

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